# Physical-Biological-Optics Model Development and Simulation for the Pacific Ocean and Monterey Bay, California

Fei Chai
School of Marine Sciences, 5706 Aubert Hall
University of Maine, Orono, Maine 04469
phone: (207) 581-4317     fax: (207) 581-4990     email: fchai@maine.edu

Emmanuel Boss
School of Marine Sciences, 5706 Aubert Hall
University of Maine, Orono, ME 04469
phone: (207) 581-4378     fax: (207) 581-4990     email: emmanuel.boss@maine.edu

## LONG-TERM GOALS

Modeling and predicting ocean optical properties requires linking optical properties with the physical, chemical, and biological processes in the upper ocean. Our long-term goal is to incorporate optical processes into coupled physical-biological models for both open ocean and coastal waters, develop and improve integrated ocean forecasting systems, including prediction of ocean optical properties.

## OBJECTIVES

1) To improve performance of the coupled physical-biological model, which is based on the Navy Coastal Ocean Model (NCOM) for the California Current System and Regional Ocean Model System (ROMS) for the Pacific Ocean;

2) To incorporate optical variables into the improved coupled 3D physical-biological model for the Pacific Ocean and California Current System;

3) To evaluate physical-biological-optical models with remote sensing and available in situ observations;

4) To use these variables to drive a radiative transfer model (EcoLight) that will simulate and predict the subsurface light field as well as the ocean's color.
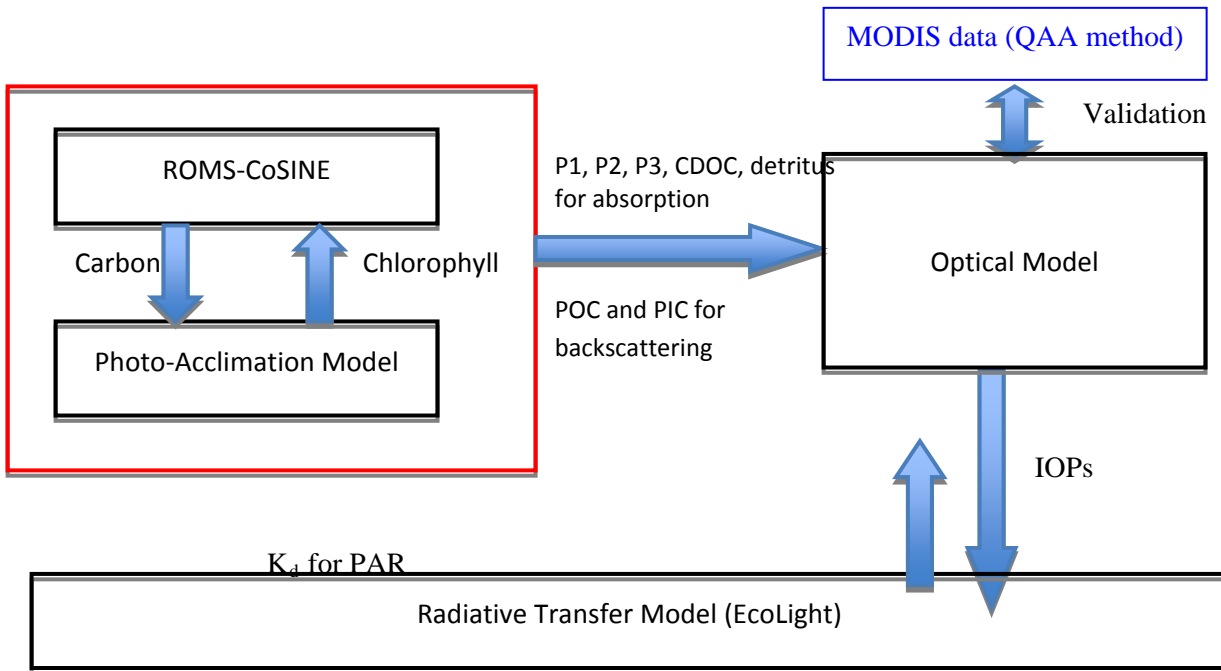
## APPROACH

To achieve the first objective, we have conducted a series of 3D physial-biological model simulations for the Pacific Ocean and California Current System. We have incorporated the Carbon, Silicate, and Nitrogen Ecosystem (CoSiNE) model into both the Navy Coastal Ocean Model (NCOM) and Regional Ocean Model System (ROMS). The CoSiNE model (Chai et al., 2002; 2003, and 2007) was developed originally for the equatorial and Pacific Ocean. During the past several years, we have implemented

| 1. REPORT DATE **2009** | 2. REPORT TYPE | 3. DATES COVERED **00-00-2009 to 00-00-2009** |
|---|---|---|

| 4. TITLE AND SUBTITLE **Physical-Biological-Optics Model Development and Simulation for the Pacific Ocean and Monterey Bay, California** | | 5a. CONTRACT NUMBER |
|---|---|---|
| | | 5b. GRANT NUMBER |
| | | 5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | | 5d. PROJECT NUMBER |
| | | 5e. TASK NUMBER |
| | | 5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Maine,School of Marine Sciences,5706 Aubert Hall,Orono,MA,04469** | | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | | 10. SPONSOR/MONITOR'S ACRONYM(S) |
| | | 11. SPONSOR/MONITOR'S REPORT NUMBER(S) |

12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT **unclassified** | b. ABSTRACT **unclassified** | c. THIS PAGE **unclassified** | **Same as Report (SAR)** | **9** | |

the CoSiNE model and improved the performance, and investigated the seasonal and interannual variation of biological productivity in response to both local and remote climate forcing (Chai et al., 2009; Liu and Chai, 2009a, b).

To simulate optical variables with the improved coupled 3D physical-biological model, we incorporate spectrally-resolved inherent optical properties (IOPs) into the existing ROMS-CoSiNE model, which haven't included the optical processes and in-water radiative transfer model yet (see Figure 1). We have successfully incorporated an optical module along with a commercially available radiative transfer model (EcoLight) into a one-dimensional ecosystem model which is flexible enough that can be applied to three-dimensional circulation model (Fujii et al., 2007). We are collaborating with Dr. Curt Mobley at Sequoia Scientific to implement the updated version of EcoLight into the ROMS-CoSiNE model. To start, we will use an idealized test bed framework for 3D ROMS-CoSiNE model. Recently, the CoSiNE model has been fully incorporated into the standard ROMS code, and the CoSiNE model results have been evaluated and compared with several other ecosystems models that already imbedded into the ROMS. Later phase of our collaboration with Dr. Mobley will imbed EcoLight into the ROMS-CoSiNE model for application to the Pacific Ocean and California Current System.

The optical model explicitly represents spectrally-resolved IOPs including absorption, scattering, and attenuation. The optical model requires input from ROMS-CoSiNE model, such as phytoplankton associated chlorophyll and non-algal particles (NAP), and it provides outputs such as phytoplankton absorption coefficient, detritus absorption coefficient, particulate backscattering coefficient. These optical products are all spectrally-resolved and can be compared with satellite and in situ data directly.



*Figure 1: Overall approach for incorporating optical properties into the coupled three-dimensional ROMS-CoSiNE model. P1, P2, P3, POC, PIC, and CDOC denote pico-plankton, diatom, coccolithophorids, particulate organic carbon, particulate inorganic carbon and color dissolved organic carbon, respectively.*

Since the last annual report, we started developing an optical model that is fully compatible with ROMS-CoSiNE and NCOM-CoSiNE model, which explicitly represents spectrally-resolved IOPs. However, the weakness of the early model is that the color dissolved organic matter (CDOM) was set constant at that time due to its complicated optical and biogeochemical properties. CDOM plays an important role in absorption spectra both in the open ocean and coastal regions. In order to improve the existing model and try to simulate CDOM dynamics, we have modified CoSiNE model and incorporated color dissolved organic carbon (CDOC) as a state variable, which is expressed as:

$$BIOLOGY(CDOC) = BIOLOGY(P) + BIOLOGY(Z) + BIOLOGY(B) - UVlight \tag{1}$$

Here, CDOC is mainly produced by phytoplankton (P), zooplankton (Z) and bacteria (B) through their biological processes such as grazing loss, excretion, and mortality etc. CDOC is destroyed by the UV light only, which is a function of the light attenuation coefficient ($k_d$) at 300 nm:

$$UVlight(z) = a_{CDOC}(410, z) \times R \times \exp[-\int_0^z k_d(300, z)dz] \tag{2}$$

where R is the coefficient, $a_{CDOC}(410)$ is the CDOC absorption coefficient which can be related to CDOC concentration by

$$a_{CDOC}(410) = a^*_{CDOC}(410) \times CDOC \tag{3}$$

where $a^*_{CDOC}(410)$ is the specific CDOC absorption coefficient at 410 nm. Then for the whole visible spectra, CDOC is modeled as

$$a_{CDOC}(\lambda) = a_{CDOC}(410) \times \exp\{-0.0145 \times (\lambda - 410)\} \tag{4}$$

In order to better simulate water optical properties, we also included coccolithophorids as a state variable in the CoSiNE model. Phytoplankton absorption spectra is then modeled as:

$$a_\phi(\lambda, z) = a^*_{\phi 1}(\lambda, z) \times chl1(z) + a^*_{\phi 2}(\lambda, z) \times chl2(z) + a^*_{\phi 3}(\lambda, z) \times chl3(z) \tag{5}$$

where chl1, chl2, and chl3 is pico-plankton, diatom, coccolithophorids, respectively. $a^*_\Phi$ is chlorophyll-specific absorption coefficient, which is modeled as When taking into account phytoplankton photo-adaptive stage:

$$a^*_{\phi 1}(\lambda) = a^*_{\phi 1(high\ light)}(\lambda) \times (1 - \frac{\theta_{s1} - \theta^C_{min}}{\theta^C_{max} - \theta^C_{min}}) + a^*_{\phi 1(low\ light)}(\lambda) \times \frac{\theta_{s1} - \theta^C_{min}}{\theta^C_{max} - \theta^C_{min}} \tag{6}$$

$$a^*_{\phi 2}(\lambda) = a^*_{\phi 2(high\ light)}(\lambda) \times (1 - \frac{\theta_{s2} - \theta^C_{min}}{\theta^C_{max} - \theta^C_{min}}) + a^*_{\phi 2(low\ light)}(\lambda) \times \frac{\theta_{s2} - \theta^C_{min}}{\theta^C_{max} - \theta^C_{min}} \tag{7}$$

where $a^*_{\phi 1(high\ light)}(\lambda)$, $a^*_{\phi 1(low\ light)}(\lambda)$, $a^*_{\phi 2(high\ light)}(\lambda)$, and $a^*_{\phi 2(low\ light)}(\lambda)$ are chlorophyll-specific absorption coefficient at high and low light conditions by each phytoplankton, respectively. $\theta^C_{min}$ and $\theta^C_{max}$ are the minimum and maximum phytoplanktonic chlorophyll to carbon ratios. $\theta_{s1}$ and $\theta_{s2}$ are chlorophyll to carbon ratios for pico-plankton and diatoms, respectively. Note that, we assume coccolithophorids do not have photo-adaptive effect in the current model.

In the optical model, assuming no contribution of CDOM to backscattering, backscattering coefficient is determined as the sum of seawater, algae and co-varying particles. Algae and co-varying particles are expressed as a function of particulate organic carbon concentration (POC) and particulate inorganic carbon (PIC) of small and large particles, which consist of pico-plankton, diatoms, coccolithophorids and associated NAP, respectively. Backscattering by small and large POC (POC1 and POC2) and PIC are formulated as follows (Stramski et al., 1999; Balch et al., 1996):

$$b_{bp1}(\lambda, z) = (\frac{POC1(z)}{476935.8})^{\frac{1}{1.277}} \times (\frac{\lambda}{510})^{-0.5} \tag{8}$$

$$b_{bp2}(\lambda, z) = (\frac{POC2(z)}{17069.0})^{\frac{1}{0.859}} \tag{9}$$

$$b_{bp3}(\lambda, z) = (1.6 \times PIC(z) - 0.0036) \times (\frac{546}{\lambda})^{1.35} \tag{10}$$

The total backscattering coefficient is calculated

$$b_b(\lambda, z) = 0.5 b_{sw}(\lambda) + b_{bp1}(\lambda, z) + b_{bp2}(\lambda, z) + b_{bp3}(\lambda, z) + b_{bbg} \tag{11}$$

where $b_{sw}(\lambda)$ is seawater scattering coefficient with the correction for salts (Boss and Pegau, 2001). $b_{bbg}$ is the background backscattering coefficient the implicitly reflects contributions by non-phytoplankton-covarying bacteria and other particles (Behrenfeld et al., 2005).

**WORK COMPLETED**

This report summarizes modeling activities between 1 October 2008 and 30 September 2009.

We have completed the following modeling tasks:

1. Evaluated the 3D ROMS-CoSiNE model performance for the Pacific Ocean and compared the model results with available in situ observations on nutrients, phytoplankton, and carbon fluxes (Chai et al., 2009, Liu and Chai, 2009a,b, Bidegare et al., 2009; Palacz et al., in press).

2. Linked the bio-optical module, based on 1D configuration (Fujii et al., 2007), with the ROMS-CoSiNE model, and incorporated CDOC into the CoSiNE and bio-optical module for the Pacific Ocean;

3. Evaluated the ROMS-CoSiNE-Optical model results with remote sensing derived IOPs for the Pacific Ocean;

4. Incorporated bio-optical module and CoSiNE into the Navy Coastal Ocean Model (NCOM) for the California Current System (CCS);

5. Started collaboration with Dr. Curt Mobley to incorporate EcoLight into an idealized ROMS-CoSiNE model.

**RESULTS**

We have conducted a series of the ROMS-CoSiNE model, without the optical component, for the Pacific Ocean for the period of 1990 to 2008. For doing so, we can evaluate the ROMS-CoSiNE model results with available observations, and then improve the CoSiNE model performance. For example, we compared the modeled nutrients, phytoplankton biomass, and carbon fluxes with the South East Asia Time-Series Station (SEATS) in the South China Sea (Liu and Chai, 2009a, Chai et al., 2009). We evaluated the ROMS-CoSiNE model results with the Hawaii Ocean Time-Series (HOTS) and addressed how ecosystem responded to Pacific decadal climate changes (Polovina et al., 2008, Bidigare et al., 2009). We discussed how the ROMS-CoSiNE model responds to 1997-98 El Nino event in the Japan/East Sea (Liu and Chai, 2009b). We calculated the nutrient transports and their impact on phytoplankton productivity in the equatorial Pacific (Palacz et al., in press). Since these ROMS-CoSiNE model results have been published in the peer-reviewed journals, we are not including these results in this report. Here, we report the results related to the optical model development and model evaluation with remote sensing observations.

Performances of the coupled ROMS-CoSINE-Optics model are evaluated by comparing the model results with synchronous MODIS AQUA measured data provided by NRL. There are a lot of algorithms being used to calculate ocean optical properties from satellite data. What we used for the model-satellite data comparison is the one called quasi-analytical algorithm (QAA), which is a promising algorithm for deriving inherent optical properties from ocean color. Figure 2 shows the data comparison between model and satellite for January 2006. Spatial averaged (domain shown in Fig. 2) total absorption a is 0.035 ($m^{-1}$) at 440 nm from the model results, and 0.03 ($m^{-1}$) at 443 nm for the MODIS data (based on QAA); CDOM absorption coefficient is 0.025 ($m^{-1}$) at 410 nm for the model and 0.018 ($m^{-1}$) at 412 nm for the MODIS data; the particulate backscattering coefficient $b_{bp}$ is 0.003 ($m^{-1}$) at 550 nm for the model and 0.002 ($m^{-1}$) at 555 nm for the MODIS data. Overall, the optical model produced the IOPs tend to agree well with the MODIS derived results in terms of the magnitude and spatial patterns. We continue to adjust the parameters values and model structure to improve the model performance based on the remote sensing derived IOPs.

5
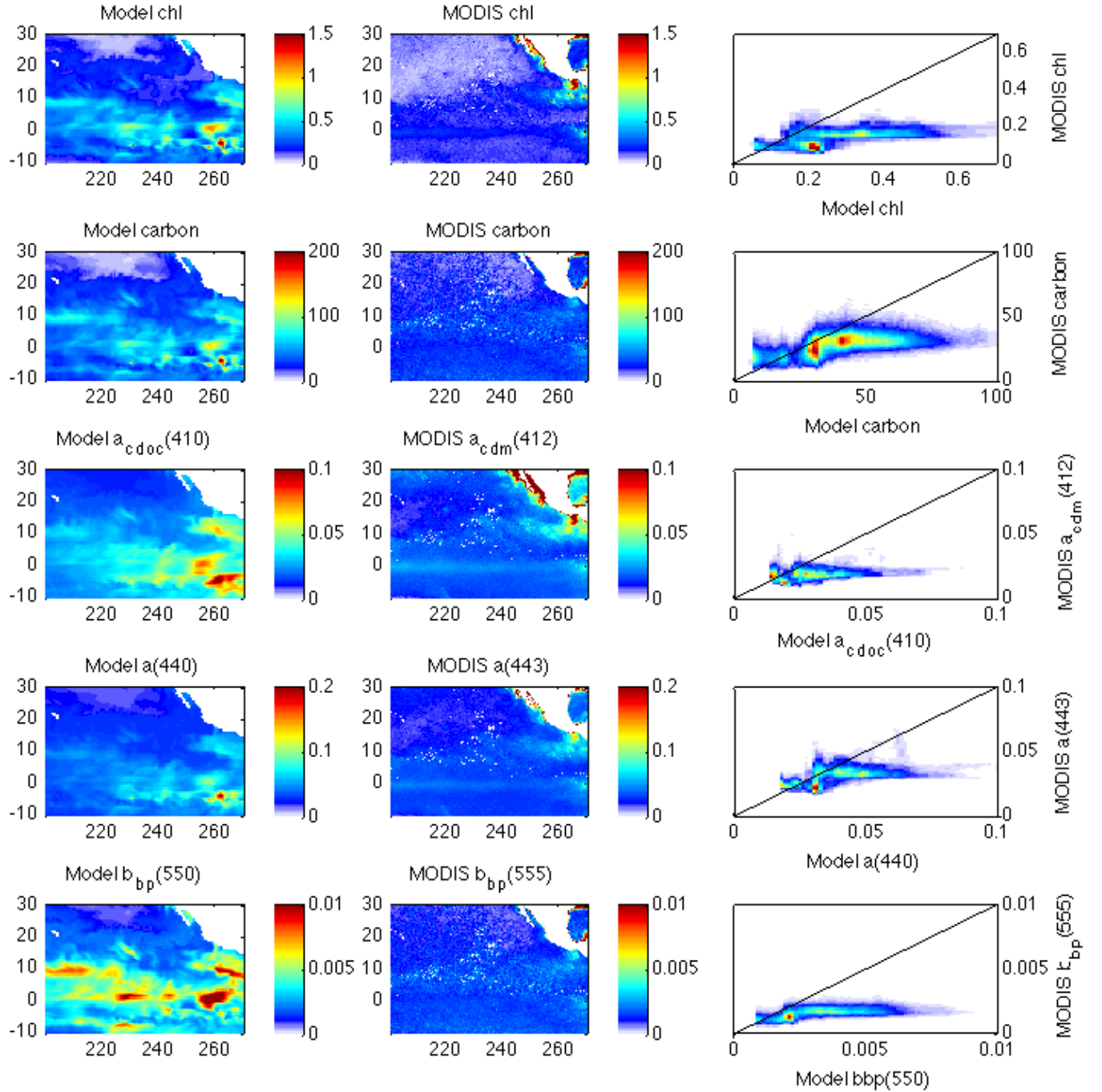
***Figure 2: Monthly (January 2006) averaged comparison between the modeled and QAA derived chlorophyll concentration, particulate organic carbon, CDOM absorption coefficient at 410 nm, total absorption coefficient at 440 nm, and particulate backscattering coefficient at 550 nm $b_{bp}(550)$. The left column is the ROMS-CoSINE-optics model outputs, the central column is MODIS QAA products, and the right column is the statistical comparison. The colors in the statistical analysis (the right column) denote the density distribution.***

Beside the incorporation of the CoSiNE model into the ROMS, we have been collaborating with the Dynamics of Coupled Processes Section (led by Dr. Igor Shulman) at NRL to implement our CoSINE model into the Navy Coastal Ocean Model (NCOM) for the California Current System (CCS). The coupled physical and biological model assimilates remote sensing information, and produces near-real time simulations on regular basis. The physical-biological model results can be viewed and obtained directly from the NRL website (http://www7320.nrlssc.navy.mil/biospace/ModelingApproach.html). Penta et al. (2008) used the NCOM-CoSiNE model results to link with a new model for simulating underwater light attenuation, which improves the model performance for the Monterey Bay. The simulation of a deep chlorophyll maximum demonstrates the effect of the new light model at depth (Penta et al., 2008). We continue our collaboration with NRL group, and will send our modified version of CoSiNE-Optical codes at regular bases.

**IMPACT/APPLICATIONS**

Incorporating ocean optical processes into coupled physical-biological models will enable us to simulate and forecast optical properties in coastal waters. With demonstration of some initial successes of developing physical-biological-optical modeling and data assimilation capability for the Pacific Ocean and California Current System, we should be able to start the development of an end-to-end ocean forecasting system. Such modeling system would be a powerful tool to design the adaptive sampling strategy and would be an essential component of future field experiments both in and outside Monterey Bay.

**TRANSITIONS**

We have been working with Drs. Igor Shulman, Bred Penta, and Sergio Derada at the Naval Research Laboratory (NRL). The ecosystem model code has been transferred to the Dynamics of Coupled Processes group (led by Dr. Igor Shulman) at the NRL. Once the optical module is fully tested with the CoSiNE, then the optical module along with the updated version of CoSiNE model will be transferred to NRL.

**RELATED PROJECTS**

This project has strong collaboration with other ONR supported projects. Besides working closely with the modeling group at the NRL and their BioSpace project, we are collaborating with Dr. Curtis Mobley of Sequoia Scientific on improving the link between the radiative transfer model (EcoLight) within the ROMS-CoSiNE-Optics. Recently, Dr. Mobley has obtained a grant from ONR to improve the efficiency of the EcoLight calculation in the 3D framework. We are also collaborating with scientists at the Monterey Bay Aquarium Research Institute (MBARI) to use the observational data for the region. Dr. Yi Chao at JPL has been collaborating with us about implementing the CoSiNE into the ROMS for the Pacific Ocean and the CCS.

**REFERENCES**

Balch, W.M., K.A. Kilpatrick, P.M. Holligan, and C. Trees (1996): The 1991 coccolithophore bloom in the central North Atlantic I – Optical properties and factors affecting their distribution. Limnology and Oceanography, 41: 1669-1683.

Behrenfeld, B., E. Boss, D.A. Siegel, and D.M. Shea (2005): Carbon-based ocean productivity and phytoplankton physiology from space. Global Biogeochemical Cycles 19, doi:10.1029/2004GB002299.

Bidigare, R.R., **F. Chai**, M. R. Landry, R. Lukas, C. Hannides, S. J. Christensen, D.M. Karl, L.Shi and Y. Chao (2009): Subtropical ocean ecosystem structure changes forced by North Pacific climate variations. *Journal of Plankton Research*, in press.

Boss, E., and W.S. Pegau (2001): Relationship of light scattering at an angle in the backward direction to the backscattering coefficient. Applied Optics 40, 5503-5507.

Chai, F. G. Liu, H. Xue, L. Shi, Y. Chao, C-T Tseng, W-C Chou, and K-K Liu (2009): Seasonal and Interannual Variability of Carbon Cycle in South China Sea: a Three-Dimensional Physical-Biogeochemical Modeling Study. *Journal of Oceanography,* Vol. 65, pp. 703 to 720.

Chai, F., M-S Jiang, Y. Chao, R.C. Dugdale, F. Chavez, and R.T. Barber (2007): Modeling Responses of Diatom Productivity and Biogenic Silica Export to Iron Enrichment in the Equatorial Pacific Ocean. *Global Biogeochemical Cycle*, Vol. 21, GB3S90, doi:10.1029/2006GB002804.

Chai, F., M. Jiang, R.T. Barber, R.C. Dugdale, and Y. Chao (2003): Interdecadal Variation of the Transition Zone Chlorophyll Front, A Physical-Biological Model Simulation between 1960 and 1990. *Journal of Oceanography,* Vol. 59, 461-475.

Chai, F., R. C. Dugdale, T-H Peng, F. P. Wilkerson, and R. T. Barber (2002): One Dimensional Ecosystem Model of the Equatorial Pacific Upwelling System, Part I: Model Development and Silicon and Nitrogen Cycle. *Deep-Sea Res. II*, Vol. 49, No. 13-14, 2713-2745.

Fujii, M., E. Boss, and F. Chai (2007): The value of adding optics to ecosystem models: a case study. Biogeosciences 4, 1585-1631. The paper can be downloaded at the Biogeosciences website: http://www.biogeosciences-discuss.net/4/1585/2007/bgd-4-1585-2007.pdf

Lee, Z., K. L. Carder, and R. A. Arnone, "Deriving inherent optical properties from water color: a multiband quasi-analytical algorithm for optically deep waters," Applied Optics. 41, 5755-5772 (2002).

Liu, G. and F. Chai (2009a): Seasonal and interannual variability of primary and export production in the South China Sea: A three-dimensional physical-biogeochemical model study. ICES *Journal of Marine Science*, 66, 420-431.

Liu, G. and F. Chai (2009b): Seasonal and interannual variation of physical and biological processes during 1994-2001 in the Sea of Japan/East Sea: a three-dimensional physical-biogeochemical modeling study. *Journal of Marine Systems*, Vol. 78, 265-277.

Palacz, A.P., F. Chai, R.C. Dugdale, and C.I. Measures (in press): Estimating iron and aluminum removal rates in the eastern equatorial Pacific Ocean using a box model approach. Deep Sea Research II.

Penta, B., Z. Lee, R.M. Kudela, S.L. Palacios, D.J. Gray, J.K. Lolliff, and I.G. Shulman (2008): An underwater light attenuation scheme for marine ecosystem models. Optics Express, Vol. 16, No. 21, 16581-16591.

Polovina, J. J., F. Chai, E. A. Howell, D. R. Kobayashi, L. Shi, and Y. Chao (2008): Ecosystem dynamics at a productivity gradient: a study of the lower trophic dynamics around the northern atolls in the Hawaiian Archipelago. *Progress in Oceanography*, 77, 217-224.

Stramski, D., R.A. Reynolds, M. Kahzu, and B.G. Mitchell (1999): Estimation of particulate organic carbon in the ocean from satellite remote sensing. Science, 285, 239-242.